Thermal-mechanical modeling of in situ thermal tests in the Yucca Mountain ESF

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Objectives

A finite-difference code was used to calculate changes in temperatures, stresses, and displacements for 2D models of in situ thermal tests being conducted in the Exploratory Studies Facility (ESF) at Yucca Mountain, NV. The objectives of the modeling were to investigate coupled thermal-mechanical (TM) processes that may occur in the near-field environment of a repository, to provide information for designing future ESF tests, and to use TM modeling results in the interpretation of results from thermal-hydrological (TH) modeling.

Approach

The code FLAC (written by Itasca Consulting Group, Inc.) was used to simulate two tests in the ESF, the Single Heater Test (SHT) and the Drift-Scale Test that includes wing heaters (DST). The rock was modeled as a homogeneous elastic medium, having the same mechanical properties as those found from laboratory measurements made on Topopah Spring tuff cores and small blocks (e.g., Blair and Berge, 1996). Thermal properties were chosen to match those used in TH modeling (Buscheck and Nitao, 1995). The SHT model represented a two-dimensional 60 m x 60 m region using 1400 grid elements with smallest grid spacing of about 0.1 m in the central part of the model. The FLAC model geometry was intended to match that used in TH modeling, for comparison of results, and may differ from the actual ESF test geometry. The DST model was about 80 m x 90 m and used 2170 grid elements, with similar grid spacing. For the canister heaters in the SHT model that Buscheck and Nitao (1995) represented using a 2.1 kw/m linear heat source, the FLAC model used interior sources within grid elements having finite cross-sectional areas. The SHT model simulated a heat source of 0.9-m-radius canister heaters aligned perpendicular to the model in the center of a 5 m x 5 m drift, with total power of 827 w/m^2 per m in the direction perpendicular to the model. (This value is 2.1 kw/m divided by the cross-sectional area of a circle having a radius of 0.9 m.) Similarly, the DST model used canister heaters with total power of 314 w/m^2 per m in the direction perpendicular to the model, equivalent to the 0.8 kw/m line source used by Buscheck and Nitao (1995). The DST model also included 150 w/m^2 per m and 225 w/m^2 per m wing heaters in a plane perpendicular to the model and extending about 4 to 14 m from the center of the drift. These represent the wing heaters that Buscheck and Nitao modeled using planar heat sources having areal power densities of 105 w/m^2 and 157.5 w/m^2 in planar sections 5 m wide. The temperature fields and resulting stresses and displacements were calculated for 0.5, 1, 2, 3, and 4 years of heating, for comparison to results from TH modeling (Buscheck and Nitao, 1995).

Results and Significance

After heating, the region in the SHT model having temperatures above 100°C formed a circle centered on the line of canister heaters, with approximate radius of 7 m after 1 year and 10 m after 4 years. This is equivalent to the dryout zone in the TH model of Buscheck and Nitao (1995). The calculated temperature field for the DST model (Figures 1, 2) also agreed with the TH modeling results, for regions outside the heated drift. Inside the drift, the temperatures in the FLAC model and peak temperature at the center of the heater were higher than those for the TH model, because FLAC used sources with finite cross-sectional areas to represent the heaters and the TH code used line sources. (Future modeling will include investigation of different representations of heat sources in the FLAC code.) The temperatures agree and thermal conductivity values match for the TH and FLAC models at the drift wall and beyond. This agreement in temperature results is promising for modeling coupled thermal-mechanical-hydrological (TMH) processes in the near-field environment. Horizontal stresses in the SHT model in the region about 3 to 30 m beyond the heater reached maximum values of about 20 to 50 MPa in compression after 1 year of heating and 30 to 70 MPa after 4 years of heating. Corresponding vertical stresses were about 10 to 40 MPa in compression after 1 year and 20 to 60 MPa after 4 years. The highest stresses in the region about 3 to 30 m from the heater were found where temperatures were highest, near the heater. Shear stresses were low, below 20 MPa for 0.5 to 4 years of heating. Horizontal displacements were up to 8 mm after 1 year and 20 mm after 4 years of heating. The vertical displacements were up to 7 mm after 1 year and 12 mm after 4 years. The DST model had similar stress results (Figure 3), except that a high stress gradient developed in the region between the drift wall and the end of the wing heater plane a few m away. Although the FLAC modeling may have overestimated stresses and displacements since the effects of fractures were ignored, this high stress gradient resulted from a high temperature gradient, and should be considered when tunnel support requirements are specified.

Potential Applications and Contributions to Rock Mechanics

The agreement between the TH and the FLAC temperature results indicates that stress and displacement results calculated using FLAC can be related to the TH modeling for these ESF tests. Coupled TMH processes also could be modeled by using the temperature fields computed by the sophisticated TH code (Buscheck and Nitao, 1995) as input for FLAC calculations of stress and displacement results. This work provides information about rock response that is needed for design of future tests at Yucca Mountain, and contributes to the understanding of coupled processes in the near-field environment of a repository.

References

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Buscheck, T. A., J. J. Nitao, 1995, Thermal-hydrological analysis of large-scale thermal tests in the Exploratory Studies Facility at Yucca Mountain, LLNL report UCRL-ID-121791, 54 pp.

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Figure 1. Temperature for DST model, thermal time 4 years.

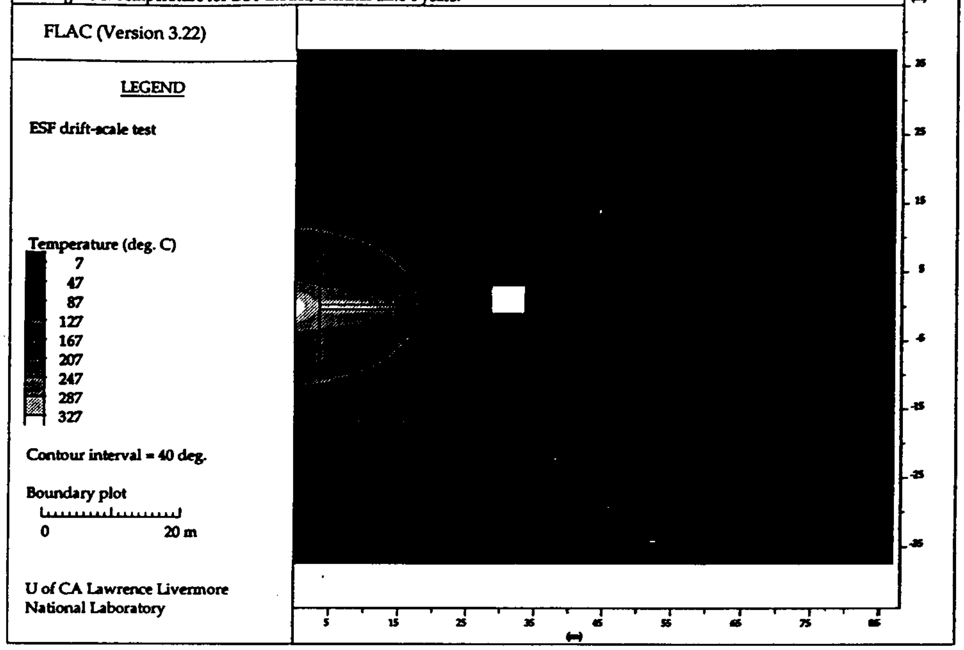

Figure 2. Vertical profile through heaters in DST model, for temperature field after 4 years of heating.

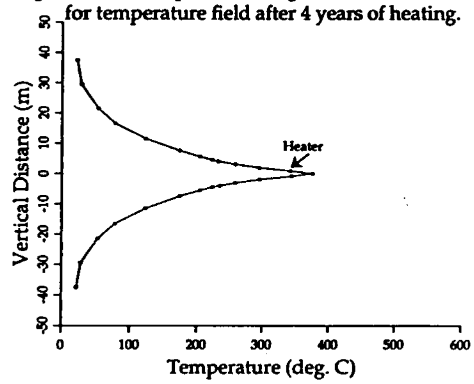

Figure 3a. Horizontal stress field, thermal time 4 years.

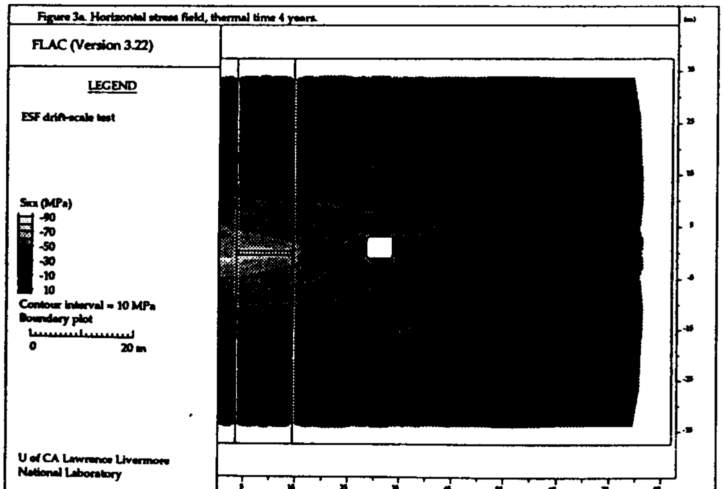

Figure 3b. Vertical stress field, thermal time 4 years.